PROGRESS REPORT

ITEM #0001AB

DECEMBER 1994

DEVELOPMENT OF INJURY PREVENTING HELMET SERVO-SUPPORT SYSTEM FOR HIGH PERFORMANCE AIRCRAFT

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Section I. Purpose and Scope of the Research Effort

The technical objective of this program is the development of a support system for the aviator's helmet wherein the load created by the helmet and helmet mounted equipment is removed from the aviator's head and is transferred directly to the aviator's seat and airframe. The support system, while supporting the helmet load, shall be powered and controlled to move with the aviator's head such that the helmet is retained on the aviator's head in a normal manner. The support system shall provide freedom of head movement and allow the aviator to easily control the movement of his/her head, his/her helmet and the helmet mounted equipment.

The technical objective of this program is being undertaken in the form of a multi-task program as outlined in the proposal. The objectives of the individual tasks are presented below.

1. Definition of System Parameters.

The objective of this task is to identify and establish values and/or limits for all system parameters that must be satisfied in the embodiment of the support system or that serve as factors in the development of a more reliable or optimal system. This specific information is required to ensure that project effort is properly directed toward the development of a system that will meet the overall technical objective of the program.

2. Select Optimal System Characteristics.

The objective of this task is to optimize the kinematics, control strategy, and energy requirements for the helmet support system. To facilitate this effort, a comprehensive computer simulation of the dynamic interaction between the helmet support hardware and the aviator will be developed.

3. Complete Mechanical System Layout Including Drive and Mechanical Component Selection.

The objective of this task is to complete the selection of all mechanical components, provide the specifications for the selected components and provide design layouts establishing the proper assembly, clearances, fit and functions of all components within the proposed design. Utilizing the system parameters as defined in Task 1 and the design optimization results determined in Task 2, this task serves as the means to establish component and design details in light of

A-1

specific requirements and to select components that thereby optimize the design of the mechanical system.

4 Complete the Electrical Control System Layout Including Component Selection and Determination of System Characteristics.

The objective of this task is to complete the design of the helmet support control system to satisfy the performance requirements identified in Task 1. To facilitate this effort, the proposed control system will be optimized through an iterative analysis with a modified head-spine mathematical model (HSM).

The foregoing provides for the development of the helmet servo-support system for high performance aircraft in accordance with the proposed effort.

Section II. Overall Progress To Date

The technical objective of this program is being undertaken in the form of a multi-task program as outlined in the proposal. Progress has been made in each of the tasks as presented below.

1. Definition of System Parameters.

The identification of the parameters for the helmet support system and the selection of practical limits or values for these parameters is essentially completed. The appropriate system parameters and corresponding values or limits for each of these parameters is based on a review of the available literature and an evaluation of both the dynamic and spatial requirements of the head support. The literature that is currently available does not address the specific requirements of a servo-controlled head support. As such, the system parameters are developed from the specifications that are available for aircrew station geometry and from available anthropometric data. The system parameters selected for the design of the servo-controlled helmet support is presented in appendix "A".

2. Select Optimal System Characteristics.

The analysis of the kinematic requirements, control strategy, and energy requirements of the helmet support system is essentially completed. Alternatives have been evaluated and selections made to meet the system requirements. Considerable effort had to be provided in this task in order to develop a linkage

arrangement and control strategy that would meet the full displacement requirements of the system, provide optimal system characteristics, meet the system parameters identified in task 1 above and provide support to the helmet in accordance with the concept presented by the proposal.

A support arrangement that will provide optimal system characteristics has been selected and is shown in the mechanical system layout in appendix "B". This support arrangement supports the helmet in the same manner as the arrangement presented in the proposal with modifications incorporated into the linkage system in order to meet the displacement and spatial requirements identified in task 1 above. The support arrangement has been developed through an iterative process that included the development and analysis of various alternative arrangements.

The operating envelope or motion requirements, as established by the system parameters selected in task 1 above, and the very confined space available within the cockpit serve as design drivers in restricting possible alternative design arrangements. The very limited space between the seat and the canopy essentially eliminates the possibility of providing lateral movement of the helmet by rotating the support linkage at the base of the linkage assembly. The development of an acceptable linkage arrangement is driven also by the need to provide head support through a full 60 degrees of head rotation. The requirement for support through 60 degrees of rotation in either direction from center requires that the support linkage be able to reach around the helmet. This reaching around the helmet dictates that the support must be able to provide a large forward displacement, full rearward retraction, and significant lateral displacement as well as curving around the helmet as the support reaches around the helmet. In addition, the need to reach around the upper part of the ejection seat when rotating the head near the headrest and the very limited cockpit space as established by the aircrew station geometry places additional spatial restrictions on the design of the system.

Through the iterative process of developing and evaluating various kinematic arrangements, the support linkage shown in appendix "B" is considered to be the optimal configuration for the requirements provided in task 1. In this arrangement, the support linkage provides rotational capability of 60 degrees in either the clockwise or counter-clockwise directions by incorporating a curved link that is configured to reach around the helmet when the helmet is rotated. The curved link is mounted on the second arm of the support and pivots in the lateral plane in order to provide the required lateral motion as well as being able to reach around both the helmet and the seat back. A rotational capability of 60 degrees in either the clockwise or counter-clockwise directions is provided by this support linkage. An additional stage of rotation can be provided between the arm support and the helmet and thus incorporate an additional and desirable 30 degrees of free rotation of the head about any rotational position of the support linkage. This would provide a total head rotation capability of 90 degrees with 60

degrees of the rotation provided by the linkage support and the remaining rotation being provided by a bearing between the helmet frame and the support yoke. This alternative second stage of rotation provides additional rotation without requiring the linkage system to extend the complete distance around the head. The two stage rotation provides greater freedom for head rotation and requires that the linkage follow and reach around the helmet for 30 degrees less than actual head rotation.

A control strategy for minimizing the forces between the head and the helmet while allowing freedom of head movement has been devised. The control strategy consists of a sensory technique for evaluating the forces between the head and the helmet by sensing the forces between the support point of the helmet and the two supporting arms. The force levels sensed at the support points are compared with the anticipated values of force level as determined by the known weight of the helmet, weight of helmet equipment, contributing weight of the support linkage and the acceleration of the aircraft. The force levels sensed at the support point, when compared to the anticipated force levels at these locations, provide the proper input to the control system in order to provide servo-control of the support forces. The sensory technique and system response characteristics are shown in appendix "C".

The objective of the control law task is to develop a hybrid force and position control system that will direct the mechanical linkage system so that the inertial loading of the helmet is removed from the pilots head. Currently the focus of the control task has been on both the modeling and control law development at the interface between the linkage end effector, helmet and the head. Appendix C summarizes the current model used for simulation along with the control strategy development and preliminary simulation results. Initial results show that the head-helmet-end effector system is completely controllable from the point of view that there are no ranges of motion that cannot be achieved by appropriate control action and also the system is completely observable from a measurement of the contact force between the end effector and the helmet.

Control of the head-helmet force is achieved via the application of a Linear Quadratic Regulator coupled with a Kalman Filter (LQR-KF) to both regulate and estimate the states (i.e. contact forces between the head and the helmet) of the system. By definition of an appropriate performance index that incorporates the head-helmet contact force and subsequent minimization of this performance index yields a control strategy that involves the on-line solution of the standard Riccati equation. Through the selection of a variable control weighting parameter one can select the level of contact force to remain between the head and the helmet. Simulation results show that the effects of measured aircraft accelerations on the head-helmet contact force can be reduced significantly (see Figures C.2 - C.4 of Appendix C). In addition, the LQR-KF control strategy has demonstrated the

ability to allow for the unimpeded motion of the pilots head while removing the inertial loading of the helmet on the pilots head.

The energy requirements for the drive axis of the servo-support system has been estimated at one-tenth horsepower per axis and, as such, dictates the use of drive units that are somewhat larger than anticipated or desired for this installation. Various types of drives have been reviewed. The use of self-contained electro-hydraulic drive units appear to provide the best system characteristics by providing greater flexibility in matching the drive characteristics to the unique requirements of the support of the helmet. These drives have the potential for providing greater support forces without using extensive gear reduction units. The final selection of the drive units and the incorporation of the units into the design layout is being undertaken in task 3.

3. Complete the Mechanical System Layout Including Drive and Mechanical Component Selection.

Design layouts are presently being developed as shown in appendix "B". The layouts serve to identify component requirements, including the assembly, clearances, operation and functions of the components. The layout serves to evaluate the selection of components and to determine component fit within the mechanical system. Utilizing the system parameters as defined in Task 1 and the design optimization results determined in Task 2, this task serves as the means to establish component and design details in light of specific requirements and to select components that thereby optimize the design of the mechanical system.

4 Complete the Electrical Control System Layout Including Component Selection and Determination of System Characteristics.

The electrical control system is presently being developed in accordance with the review accomplished in task 2 above. This essentially involves the identification of sensors to be used to both monitor the angles of the joints of the mechanical linkage system, and measure the force levels at the end effector-helmet interface in three dimensions. Under consideration are absolute optical encoders that can measure angular rotation of two rigidly attached mechanical joints. For control strategy calculations, different families of micro-controllers, such as the Motorola MC68HC11 and the Intel based 8051, are being investigated. The main feature here is timing and clock speed. The micro-controller must have both the memory and clocking speed to take the data from both the linkage joint angles and the three dimension force levels at the end effector-helmet interface and compute the appropriate control signal to be transmitted to the drives at each joint.

The foregoing provides for the development of the helmet servo-support system for high performance aircraft in accordance with the proposed effort.

Section III. Problem Areas

1. Current Problems: System requirements, such as drive horsepower and range of motion, play a significant role in determining the size and viability of the system and these requirements must be minimized in order to provide an optimal system. However, information obtained from available literature is not adequate to determine if certain operational tradeoffs are acceptable and thus optimization of the system, at this time, is restricted. Operational aspects such range of motion, frequency of head motion and speed of head motion, contribute to the proper selection of drive horsepower and linkage arrangement. Current information on these aspects is limited and a complete operational analysis of head movement, beyond the scope of this program, is required in order to provide this information and allow for the development of a more optimal design. For this program, estimates of head motion are extrapolated from available anthropometric data. It is estimated that the limits used in the present effort represent the maximum motion encountered and therefore provides a worst case situation for the system and therefore burdens the design with movement and horsepower requirements that may be greater than necessary.

2. Anticipated Problems: None.

Section IV. Work to be Performed During the Next Reporting Period.

1. Continue the development of the mechanical system layout including drive and mechanical component selection.

2. Continue the development of the control system including component selection and evaluation of system characteristics.

3. Prepare final report.

Section V. Administrative Comments

A meeting at Conrad Technologies, Inc. facilities in Paoli, Pennsylvania is requested in order to provide a review of the technical aspects and the design details of the system with project personnel of Conrad Technologies, Inc. and a technical representative of the sponsoring agency.

APPENDIX A

SYSTEM PARAMETERS

System parameters selected to date are as follows:

1. Under flight conditions with translational accelerations less than 3g, the helmet servo-support system shall support the helmet and helmet equipment weight such that the loading between the head and helmet is reduced to less than 4.6kg force and 11,500kg-cm or less of force moment. The intent here is to support most of the helmet and helmet equipment weight but not the pilots head. The pilot controls the helmet position by applying a force or moment in the direction of the desired travel. Force moments and force levels at the occipital condyles are used as an indication of neck strain.

2. Under flight conditions with translational accelerations greater than 3g and less than 9g, the helmet servo-support system shall support all of the helmet and helmet equipment weight along with approximately 50 percent of the pilots head inertia. Under this condition, the maximum sustained force moment of the helmet and helmet equipment on the pilots head shall not exceed 34.5kg-cm. The intent here is to support the helmet and helmet equipment, to support any excess moment resulting from the helmet or helmet equipment and to assist the pilot in counteracting his/her head inertia forces. The pilot controls the helmet position by counteracting more or less than the remaining inertia forces of his/her head.

3. The helmet support system will be designed to support the helmet and helmet mounted equipment during high accelerations situations such as landing and take-off and during ejection in which accelerations may be too high for the pilot to control his/her head. It is intended that the support system will lock the helmet into an appropriate position, such as a full head back position during these intervals. The servo-support will be sized to provide full support up to 27g in the direction of ejection and 20g in the remaining directions. Insufficient data is available at this time to further define control requirements during ejection.

4. The pilots head has a limited range of motion and to avoid the possibility of injury due to forced movement of the head beyond voluntary limits of motion, motion constraints are placed on the support system. Maximum lateral travel for the helmet support is established at 12 cm. in either direction from the center position . Maximum forward travel is established at 24 cm. from a complete headback position. Maximum vertical travel is established at 5 cm. from an adjustable neutral position. Allowable yaw rotation is 60 degrees in either direction from a center position. Allowable lateral flexion is established at 30 degrees in either direction from the center position. Allowable dorsiflexion is 45 degrees and allowable ventriflexion is established at 30 degrees.

5. Force levels between the head and helmet will be managed by the control system within the motion limits of the support system. Force constraints and displacement constraints will be introduced into the support system by the control system to mitigate any problem with forced motion within the motion limits of the

support system. Force levels will be managed in general accordance with items #1, #2, and #3 above.

6. Maximum rotational pitch acceleration of the aircraft is established at 6 rad/sec. Maximum rotational roll acceleration of the aircraft is established at 6 rad/sec. Values for rotational acceleration in yaw were not found and are expected to be not significant.

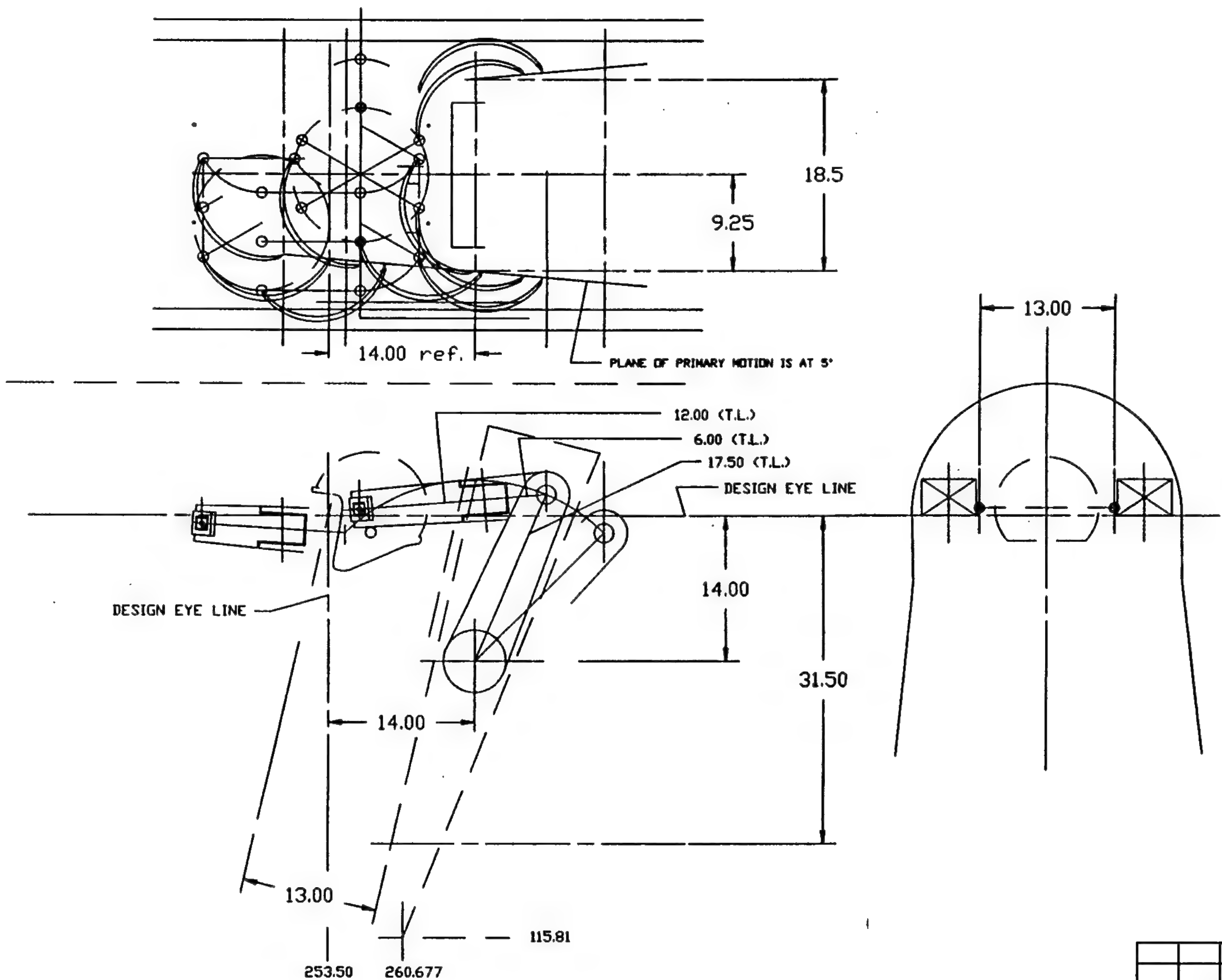
7. Range of lateral motion of the upper torso of the pilot within the shoulder harness of the aircraft seat is established at a maximum of 12 cm. in either lateral direction from the center position. Range of vertical motion of the upper torso at the base of the neck is established at 5 cm. in either direction from an adjustable neutral position. The range of forward motion of the upper torso from a full back position is established at 12 cm.

8. Maximum head weight is established at 5.257 kg. Minimum head weight is established at 3.676 kg. The principal moments of head inertia range from 155.8 to 260.0 kg-cm for head roll, 174.3 to 310.0 kg-cm for pitch and 122.5 to 191.6 for yaw rotation.

9. Maximum helmet and helmet equipment weight is established at 2.7 kg. Additional information has been requested and is not currently available on the c.g. or the moment of inertia of the helmets and helmet mounted equipment.

APPENDIX B

MECHANICAL SYSTEM LAYOUT



ITEM	QTY	SPECIFICATION / STOCK SIZE OR MANUFACTURER	MATERIAL

CONRAD TECHNOLOGIES, INC.

SURFACE FINISH 125RMS UNLESS OTHERWISE NOTED FINISHES SHOWN BY RMS SYMBOLS REF. MIL. STD.-10

BREAK ALL SHARP EDGES UNLESS OTHERWISE NOTED

TOLERANCE
FRACTIONS ±1/64
DECIMALS
.00 ±.010
.000 ±.005
ANGLES ±1/4°
UNLESS OTHERWISE NOTED

DO NOT SCALE PRINT

SIZE D	DRAWING NO		REV
DWN.	CHK.	APP.	
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APPENDIX C

CONTROL STRATEGY FOR THE HEAD-HELMET-END EFFECTOR INTERFACE

APPENDIX C
CONTROL STRATEGY FOR THE HEAD-HELMET-END EFFECTOR INTERFACE

This appendix discusses the control law development for a 3 degree-of-freedom model (3-DOF) of the head-helmet-end effector interface. To illustrate the results we shall examine a one dimension version of the 3-DOF model in detail. The model consist of three masses coupled via a spring and dashpot arrangement as shown in Figure C.1. Before delving into the details of the problem statement for control system we shall define the nomenclature for the model.

Variable	Description	Units
z_1	head position	m
z_2	helmet position	m
z_3	end effector position	m
m_1	head mass	kg
m_2	helmet mass	kg
m_3	end-effector mass	kg
k_1	head-torso spring constant	N/m
k_2	head-helmet spring constant	N/m
k_3	helmet-end effector spring constant	N/m
b_1	head-torso damper constant	N/(m/s)
b_2	head-helmet damper constant	N/(m/s)
b_3	helmet-end effector damper constant	N/(m/s)
a	acceleration of the airframe	m/s^2
u	control force applied to the end effector	N

For the model shown in Fig. C.1 the head is coupled to the torso via spring and damper k_1 and b_1, also the head is connected to the helmet via spring and damper k_2 and b_2, and the helmet is connected to the end effector via spring and damper k_3 and b_3. Once the airframe undergoes a measurable acceleration a(t), (known from measurements from the aircraft's gyroscope) each mass will then also undergo the same acceleration and the general control problem is to develop a control signal u(t), so that the inertial loading of the helmet on the head is minimized.

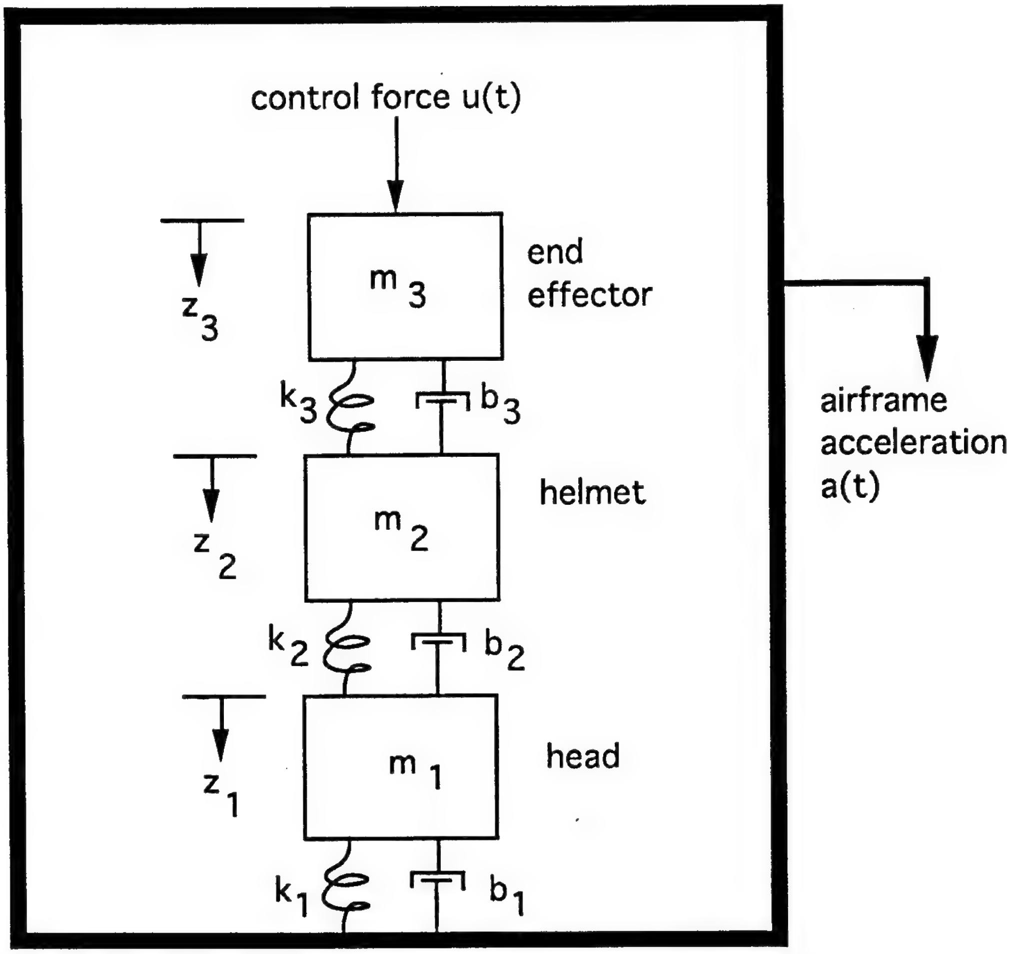

Figure C.1 Head-helmet-end effector interface model

The State Space Model. In this section the state space representation for the one-dimensional head-helmet-end effector is given for the system shown in Fig. C.1. The equations of motion are derived from applying Newton's laws of motion and are given by the following state space model

$$\dot{x} = Ax + b_1u + b_2a \qquad \text{(C.1)}$$

where

$$A=\begin{bmatrix} 0\,1\,0\,0\,0\,0 \\ -\frac{1}{m_1}(k_1+k_2) \; -\frac{1}{m_1}(b_1+b_2) \; \frac{k_2}{m_1} \; \frac{b_2}{m_1} \; 0\; 0 \\ 0\,0\,0\,1\,0\,0 \\ \frac{k_2}{m_2} \; \frac{b_2}{m_2} \; -\frac{1}{m_2}(k_2+k_3) \; -\frac{1}{m_2}(b_2+b_3) \; \frac{k_3}{m_2} \; \frac{b_3}{m_2} \\ 0\,0\,0\,0\,0\,1 \\ 0\; 0 \; \frac{k_3}{m_3} \; \frac{b_3}{m_3} \; -\frac{k_3}{m_3} \; -\frac{b_3}{m_3} \end{bmatrix}; \quad b_1=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{m_3} \end{bmatrix}; \quad b_2=\begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} \qquad \text{(C.2)}$$

and the 6-dimensional state vector is defined as $x=[x_1,x_2,x_3,x_4,x_5,x_6]^T$. Here state variables x_1 and x_2 correspond to the position and velocity of the head, x_3 and x_4 correspond to the position and velocity of the helmet, and x_5 and x_6 correspond to the position and velocity of the end effector.

Assuming that measurements are available from the contact force between the helmet and the end effector, we arrive at the following

$$y = Cx \qquad \text{(C.3)}$$

where

$$C = [0\ 0\ -k_3\ -b_3\ k_3\ b_3] \qquad \text{(C.4)}$$

Before any control design can be performed on must check the controllability and the observability of the system defined by eqns. (C.1)-(C.4). This was performed by checking the rank of the controllability and observability matrices as defined in [1, pgs. 467-473]. The rank test yielded a completely controllable and observable state space model that was then used for control system design.

The Problem Statement. Given measurements of the force between the end effector and the helmet via eqns. (C.3), and the measured acceleration of the airframe a(t), construct a control law u(t), so as to minimize the head-helmet contact force which is defined as

$$z = C_1x; \text{ where } C_1 = [k_2\ b_2\ -k_2\ -b_2\ 0\ 0] \qquad \text{(C.5)}$$

Control Law Development. There are numerous approaches that one can employ to contrstruct a control signal and we have investigated the following three: (i) output

feedback and closed loop pole assignment; (ii) Linear Quadratic Regulator; and (iii) Linear Quadratic Gaussian. Although approach (i) is the simplest to implement it was shown that under simulated turbulent conditions, where the acceleration a(t) is a random variable, the control signal cannot minimize the head-helmet contact force. Hence we have taken approaches (ii) and (iii) where we have implemented a Kalman Filter to reconstruct the unmeasured head, helmet, and end effector positions and velocities given a measurement of the helmet-end effector force given by Eq. (C.3).

Given the dynamical model of Eqns. (C.1)-(C.4) we desire to minimize the contact force given by Eq. (C.5) using optimal control theory and the following is a summary of the control calculations (for a detailed description see [2, pg. 227]). In order to minimize the contact force one can minimize the relative head-helmet positions and therefor we desire to minimize the following cost function

$$J = \frac{1}{2}x(T)S(T)x(T) + \frac{1}{2}\int_{t_o}^{T} (x^T Q x + ru^2)dt \tag{C.6}$$

where T is the final time. This is a standard quadratic cost functional which in terms of our problem we desire the minimize the relative positions and velocities in a finite amount of time denoted by T. The adjustable scalar parameter r is a term that is used to weight the cost of the control force u(t) and the weighting matrix $Q = (C_1)^T C_1$. The optimal control law that minimized the cost function of Eq. (C.6) with a measurable acceleration disturbance a(t) is given by solving the following control equations:

$$-\dot{S} = A^T S + SA - Sb_1 r^{-1} b_1^T S + Q \tag{C.7}$$

$$K = r^{-1} b_1^T S \tag{C.8}$$

$$-\dot{v} = (A - b_1 K)^T v + Sa \tag{C.9}$$

$$u = -Kx + r^{-1} b_1^T v \tag{C.10}$$

The resulting control force to be applied to the end effector is then given by Eq. (C.10) and will minimize the contact force between the head and the helmet.

Simulation Results. Simulations were performed to test the control law of Eqns. (C.7)-(C.10) for various values of the control weighting parameter r. The values used in the simulation were mass of the head $m_1 = 5$ kg., mass of the helmet $m_2 = 2$ kg., mass of the end effector $m_1 = 1$ kg., spring and damper constants were $k_1 = 1$, $k_2 = 1$, $k_3 = 1$, $b_1 = 1$, $b_2 = 1$, $b_3 = 1$, and the system was subject to various levels of disturbance accelerations. For example Figure C.2 illustrates the effector-helmet force and the head-helmet force for an acceleration $a(t) = 1$ m/s^2 when there is no applied control force at the end effector $u(t)=0$. Note from the dashed curve of Fig. C.2 that the head helmet force is relatively high (i.e. 5 N at t=8 seconds) and continues to be nonzero. Next simulations were performed with the control signal u(t) being calculated according to Eq. (C.10) and with various values of the weighting parameter r. Figure C.3 illustrates the response of the head-helmet force (dashed curve) and the effector-helmet force for a disturbance acceleration of $a(t) = 1$ m/s^2 and the control parameter r=1. Note from comparing Figs. C.2 and C.3 that the head-helmet force is reduced by a factor of 2 and the effector-helmet force is now taking the inertial loading of the helmet off of the head. Figures C.3 - C.4 illustrate the effect of varying the weighting parameter r on the response of the head-helmet force. Note that as the parameter r is increased this head-helmet force is reduced.

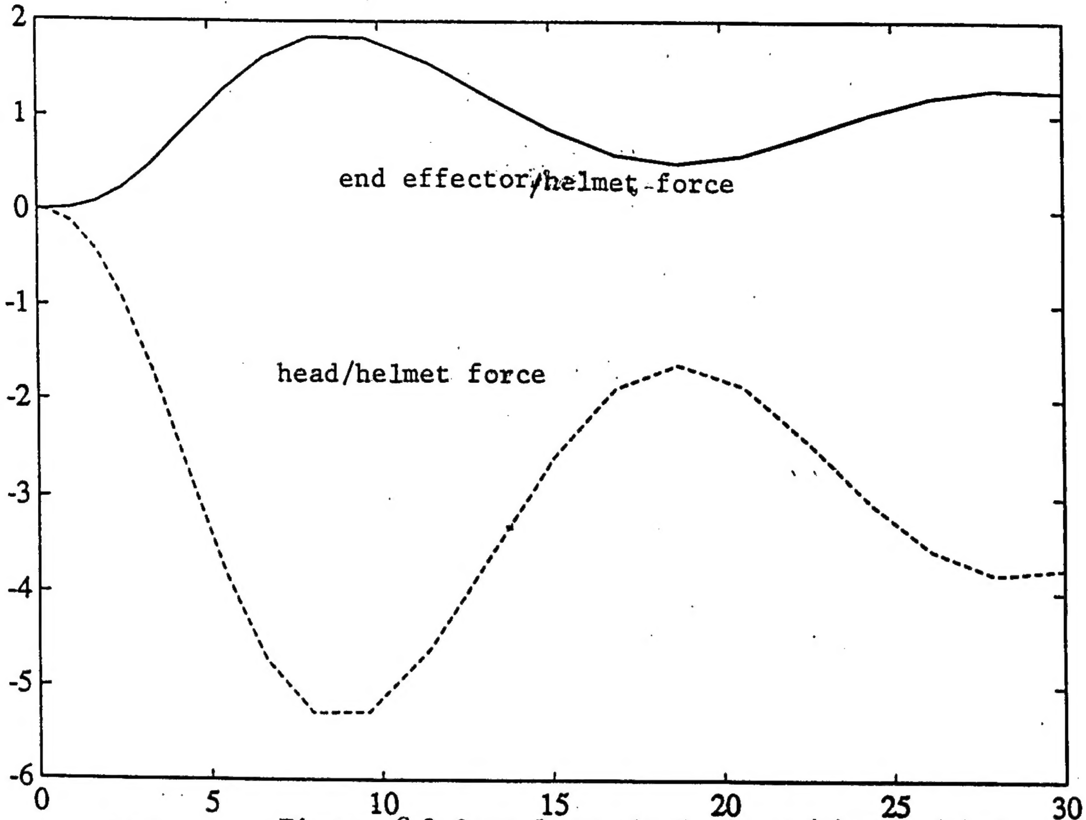

Figure C.2 Open loop simulation a(t)=1, u(t)=0

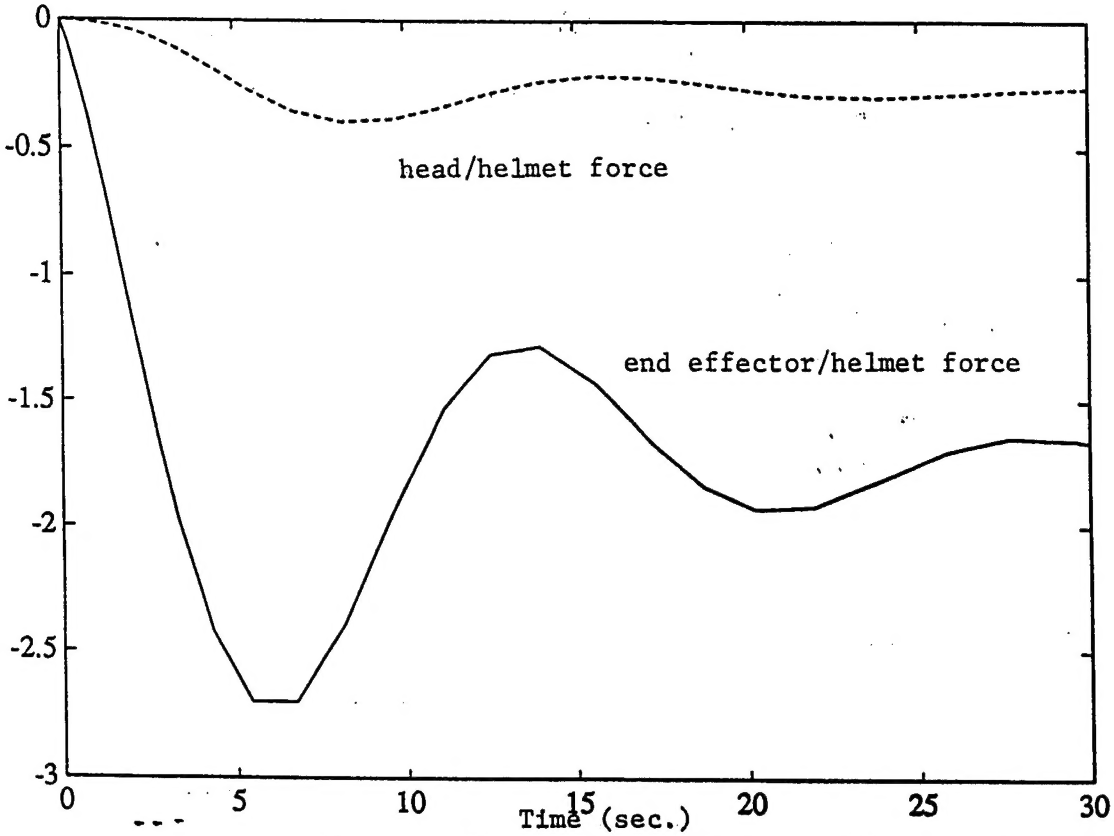

Fig. C.3 Closed loop simulation with control weighting parameter r = 10

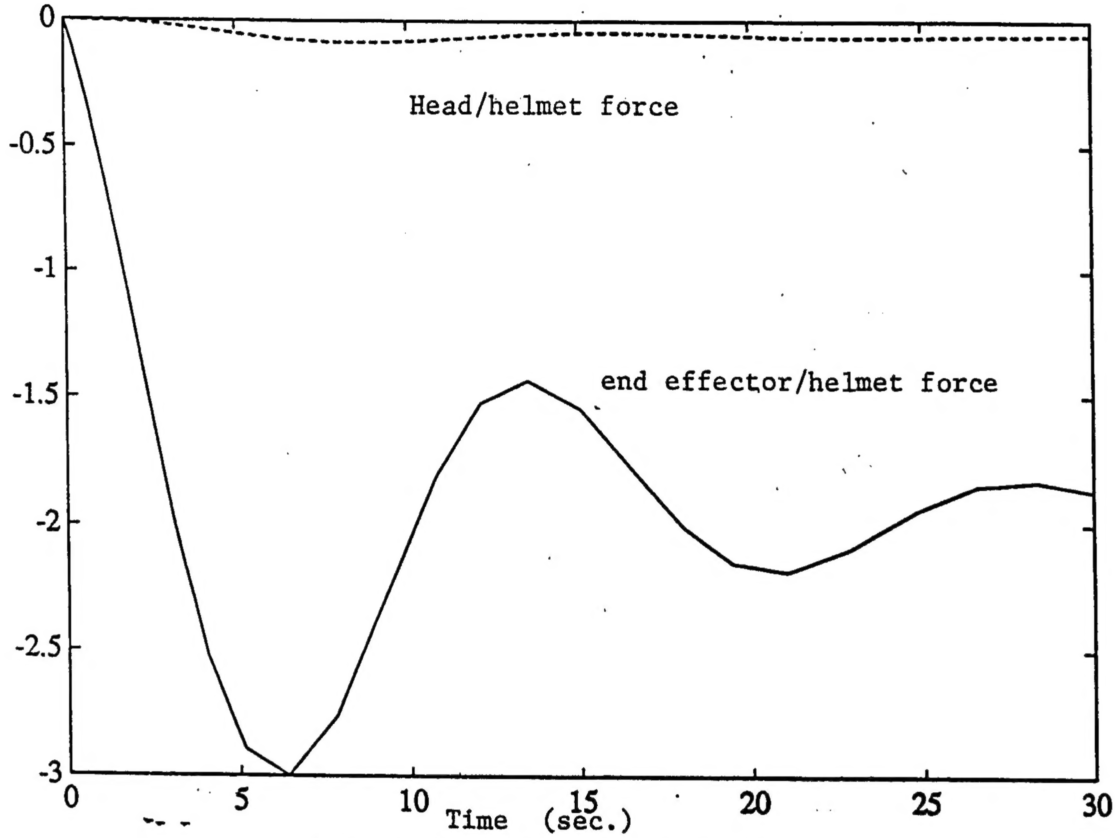

Fig. C.4 Closed loop simulation with control weighting parameter r = 50.

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[2] F. Lewis. Optimal Control. John Wiley Interscience, 1986.